HIGHWAY RESEARCH RECORD

Number 416

Lighting

3 reports

HIGHWAY RESEARCH BOARD

NATIONAL RESEARCH COUNCIL

NATIONAL ACADEMY OF SCIENCES—NATIONAL ACADEMY OF ENGINEERING

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3 reports
prepared for the
51st Annual Meeting

Subject Area
51 Highway Safety

HIGHWAY RESEARCH BOARD

DIVISION OF ENGINEERING NATIONAL RESEARCH COUNCIL
NATIONAL ACADEMY OF SCIENCES—NATIONAL ACADEMY OF ENGINEERING

Washington, D.C. 1972

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ISBN 0-309-02088-3
Library of Congress Catalog Card No. 72-12127
Price: $1.80
Available from
Highway Research Board
National Academy of Sciences
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

CONTENTS

FOREWORD

Are there proven relations between freeway illumination and traffic accidents and between city street illumination and traffic accidents? For an entire state, what are the financial implications of installing and upgrading lighting systems to be in compliance with federal guidelines? These are questions to which highway administrators, lighting designers, and traffic engineers have been seeking answers for many years. The 3 papers in this RECORD bring information of considerable value to those who must make or advise on decisions regarding the expenditure of funds for street and highway lighting systems.

The first of 2 papers by Box presents summaries of a major study of relations between accidents and lighting on city streets in Syracuse, New York. Night-day accident ratios were determined for several classes of streets, and substantial benefit-cost ratios were predicted for lighting upgrading on the various street classes. The study techniques developed will be helpful to those involved in establishing priorities for systematically upgrading illumination of city streets.

In the second paper by Box, relations between accidents and freeway illumination in several large U.S. cities are reported. Lighted freeways were found to have better (lower) night-day accident ratios than unlighted freeways. Among lighted freeways, however, those with lower levels of illumination exhibited better night-day accident ratios.

The paper by Herendeen describes the highway lighting needs study for Pennsylvania. In order to obtain information on costs, procedures were developed to facilitate rapid design of lighting where none existed but was justified, to evaluate existing lighting, and to redesign existing lighting where required. The paper presents techniques with significant potential for time savings in preliminary design and cost estimation for lighting installations.

COMPARISON OF ACCIDENTS AND ILLUMINATION

Paul C. Box, Paul C. Box and Associates, Skokie, Illinois

This paper summarizes findings from a study of illumination and accidents in Syracuse, New York. The night-day ratios of the number of accidents and the accident costs were calculated for one year of accident data (1967) and related to the illumination of each study section. Streets with little or no illumination were found to have substantially higher (poorer) night-day accident ratios and accident cost ratios than the average for all streets in the same roadway functional classification and type of abutting land use. The type of street appeared to be more of a factor in accident-illumination relation than the type of abutting land use. The methodology developed during the project is felt to represent a major contribution to the techniques in making such studies.

•A STUDY of roadway lighting in Syracuse was completed in 1970. The purposes of the project were to determine the type, amount, and priority of roadway lighting needed to reduce nighttime vehicle and pedestrian accidents and to determine the economic impact on the city of upgrading street lighting to national standards. The work included classification of each street in the city according to illumination as specified by the Illuminating Engineering Society (1). The streets were classified as major, collector, or local.

In general, local streets in Syracuse have traffic volumes of less than 2,000 vehicles per day, collector streets have volumes of 2,000 to 5,000, and major streets have volumes of more than 5,000. However, the actual function that each street serves—as a true collector or as a basic part of the major through-street system—was considered to be of at least equal significance in the classification.

The study was limited to the major and collector routes, which total 105 miles. Developments abutting these streets were checked, and the land use was classified as downtown, intermediate, or outlying areas. The downtown category includes the CBD and also secondary or neighborhood business districts. The intermediate category includes areas having some commercial activity, public buildings (schools, hospitals, and libraries), places of public assembly (auditoriums, churches, and stadiums), shopping centers, industrial areas, and retail sections having levels of activity somewhat less than that associated with downtown or community business centers. Streets abutted by major apartment developments, college dormitories, and similar high-density residential areas were classed as intermediate, for they often generate significant nighttime pedestrian traffic. The outlying areas include those where abutting land use consists of industrial, park, single-family residential, or vacant areas where little nighttime pedestrian activity is experienced.

The streets were field-checked to determine existing lighting and roadway widths. Where width, route type, or abutting land characteristics changed, separate sections were designated. Sections were further subdivided where a change occurred in lighting such as fixture size, type, mounting height, or overhang. This resulted in a total of 329 sections available for analysis.

The average maintained illumination was calculated for each section, and the length was recorded. It would have been desirable to take extensive field measurements of actual illumination, but the power company was unable to perform these checks.

The accident information was taken from the police data processing file for 1967. A computer program was developed by the Syracuse University Research Corporation to assign accidents to each roadway section.

It was impossible to pinpoint the exact location of accidents from the cards. If an accident occurred at a given intersection, it might be recorded as having occurred on either street. If both streets were included in the study, half of the accident (and its cost) could be assigned to each street. However, if the route had been divided into sections, there might be 2 or more sections involved with the same single intersection accident. Furthermore, if the intersection involved a local street that was not under study, it was impossible to determine whether the accident actually had occurred in the cross street and whether it had been influenced by the illumination level on the major or collector route section being studied.

The complications involved in using the records were extensive, and the data were less firm than we would have desired. In future work, it would be preferable to work directly from individual accident reports and to code the data on mark-sensing cards. These could then be processed through a reproducer, and regular IBM cards could be automatically punched. In this way, more details of injury and vehicular involvement, kinds of objects struck, directions of traffic movement, and legs of intersections in which rear-end accidents occurred could be simply and directly recorded.

In the Syracuse study, the accidents and costs were assigned as follows:

1. When an accident occurred at an intersection and the cross street was not in the study (i.e., it was a local street), the total cost of the accident was assigned to the appropriate section of the major or collector street and 1 accident was recorded for that section;
2. When an accident occurred at an intersection and the cross street was in the study or one section ended and another started at that intersection, the cost was divided by the number of section ends and assigned accordingly; and
3. Fractional accidents were later raised to whole numbers.

Accident records were summarized for day and night for each study section. The accident cost was estimated for the different sections as a function of the number of vehicles damaged and the number of persons killed or injured in each accident. The costs assumed for various types of accidents were taken from the Washington cost study (2).

The number of accidents and costs for each section were grouped separately by type of route and type of abutting land use. Sections having identical characteristics were consolidated.

Table 1 gives a summary of the data. The total of 3,161 night accidents and 4,334 day accidents exceeds the actual number that occurred because fractional numbers were raised to whole numbers.

ANALYSIS

The ratio of night accidents to day accidents was employed for the basic comparisons. This night-day ratio should equalize differences of traffic speeds, traffic composition, traffic volumes (to the degree not already compensated by route classification), and other variables such as type of pavement and parking characteristics. The lowest ratio of night-day accidents or accident costs indicates the best night accident experience.

For each of the classes, the sections having an illumination level at or above the 1963 specifications (1) were tabulated as group A, and those sections having lower values were tabulated as group B. Table 2 gives the night-day ratios for groups A and B. With some exceptions, group A streets had higher (poorer) accident ratios. The principal exception was class 5; but this class had only 3 percent of the route mileage and 4 percent of the accidents, and therefore this ratio was not considered significant.

The trend in the night-day ratio of accident costs was generally similar but more pronounced than for the number of accidents. However, class 6 showed a better night performance for the streets with higher illumination levels.

DETERMINATION OF OPTIMUM ILLUMINATION

The findings given in Table 2 would be expected (a) if both high- and low-illumination levels produced more hazardous driving conditions (a U-curve) or (b), alternatively, if

the number of accidents increased directly with successively increasing amounts of illumination. To check for either condition, we grouped the sections to common levels of horizontal footcandles (HFC) maintained. Ranges of 0 (unlighted) to 3.0 or greater HFC were used. Figures 1 through 3 show graphs for classes 1, 2, and 6. Figure 1 shows 2 apparent low points: The first one centers at 1.05 HFC and is produced by a total accident sample of 132, and the second one is at 1.95 HFC and is based on an accident sample of 118.

The plots of both raw and weighted data are similar. Some of the higher ratio conditions in the higher footcandle levels on the right side of the graph are associated with comparatively large numbers of accidents. It appears, however, that the accident sample in the center range of the graph was inadequate to produce a "bottom" to the curve. The optimum illumination level could be at either one of the low points or between them.

Figure 2 shows a bottom occurring between 1.65 and 1.95 HFC. Only 38 accidents were included in the sample at the lower illumination level; 107 accidents were included at the 1.95-HFC plot. Fairly large numbers of accidents were associated with data plots at both the lower and the higher footcandle levels. Furthermore, this street class has nearly twice as many accidents as class 1 and more than 4 times the mileage. Findings on illumination needs, therefore, are of more significance. These indicate that the optimum illumination for this class of street is about 1.8 HFC.

The data on collector streets were based on relatively small samples, and the points are scattered. Apparent low points of 0.75 HFC were found for class 4 and 1.05 HFC for class 5. Class 6 data are shown in Figure 3. Low points appeared at 1.05 HFC (involving only 34 accidents) and at 1.35 HFC (involving 95 accidents). The plot at 1.95 HFC involves only 8 accidents and should be disregarded.

Figure 4 shows a plot of all major and collector street data used in the study. If a common illumination level were to be specified for all these streets, the apparent low point of 1.95 HFC would indicate this to be a nominal figure. However, data plots from individual classes show that this would be an uneconomically high concentration of light for a number of conditions. Furthermore, this higher illumination level produced a poorer accident ratio for several of the classes.

The ratios and low-point data are given in Table 3. These show that illumination levels of 0.75 to 1.8 HFC appear to be appropriate for the major streets and that levels of 0.75 to 1.05 appear to be the most appropriate for the collector streets. Because of the scattered data between class 1 and class 2, these groups were combined. Also because of the small sample size in class 4 and class 5, all collector routes were combined into a single grouping.

The night-day ratios for these combinations are given in Table 4 for both the raw and weighted data. These were similar in most cases. The appropriate illumination level for classes 1 and 2 appears to be in the range of 1.65 to 1.95 HFC. (This combined plot is shown in Figure 5—310 accidents at 1.65 HFC and 225 accidents at 1.95 HFC.) The optimum illumination level should lie some place within this range, and the midpoint of these 2 groupings is 1.8 HFC.

For class 3, a level of 0.75 appears to be appropriate. For the collector routes, the midpoint of the range is 1.05.

The ratios have been checked for statistical significance. The student t-test was employed; findings for classes 1 and 2 are significant at the 99 percent confidence level, for class 3 at the 90 percent level, and for classes 4, 5, and 6 at the 95 percent level.

Data were also tabulated by street classifications. The scatter of data in the night-day accident ratios was much greater for the land use classifications, and the indication is that the area characteristic is less of a factor than street classification.

A plot of night-day accident cost ratios for the major streets was also made. The optimum points appeared in the area of 1.65 to 1.95 HFC and are thus consistent with the analysis based only on the number of accidents.

OPTIMUM ACCIDENT COST RATIOS

The ratio of night-day accident costs was found to be about 0.8 when the optimum value of 1.8 HFC is provided for classes 1 and 2. This average value prevailed when either the unweighted or the weighted cost figures were used.

Table 1. Summary of study data.

Street	Land Use Location	Class	Sections Number	Sections Percent	Accidents Night	Accidents Day	Accidents Total	Accidents Percent	Miles Number	Miles Percent
Major	Downtown	1	40	12	551	913	1,464	19	5.7	5
	Intermediate	2	68	21	1,099	1,424	2,523	34	23.0	22
	Outlying	3	69	21	679	807	1,486	20	31.5	30
Collector	Downtown	4	12	4	82	109	191	3	1.4	1
	Intermediate	5	17	5	110	189	299	4	3.0	3
	Outlying	6	123	37	640	892	1,532	20	40.7	39
Total			329	100	3,161	4,334	7,495	100	105.3	100

Table 2. IES specifications and night-day accident ratios.

Class	Specification (HFC)	Accident Ratio Group A	Accident Ratio Group B	Accident Cost Ratio Group A	Accident Cost Ratio Group B
1	2.0	0.73	0.52	2.03	0.49
2	1.2	0.79	0.76	2.06	1.54
3	0.9	1.02	0.80	1.75	0.29
4	1.2	0.87	0.64	4.80	0.75
5	0.9	0.41	0.63	0.38	1.37
6	0.6	0.72	0.72	1.08	1.37

Figure 1. Relation between illumination level and accident experience for class 1 streets.

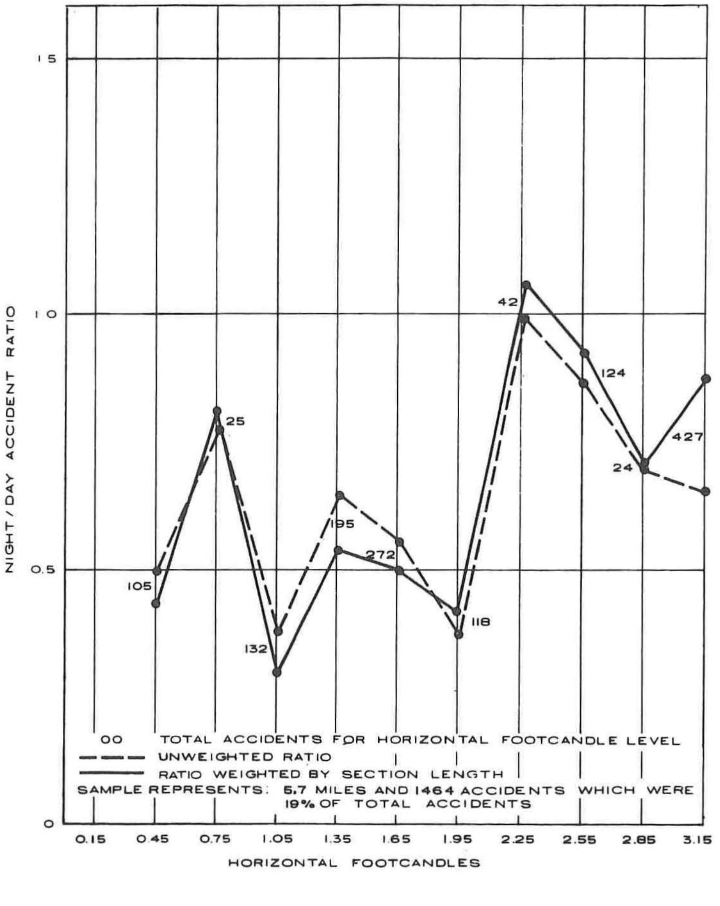


Figure 2. Relation between illumination level and accident experience for class 2 streets.

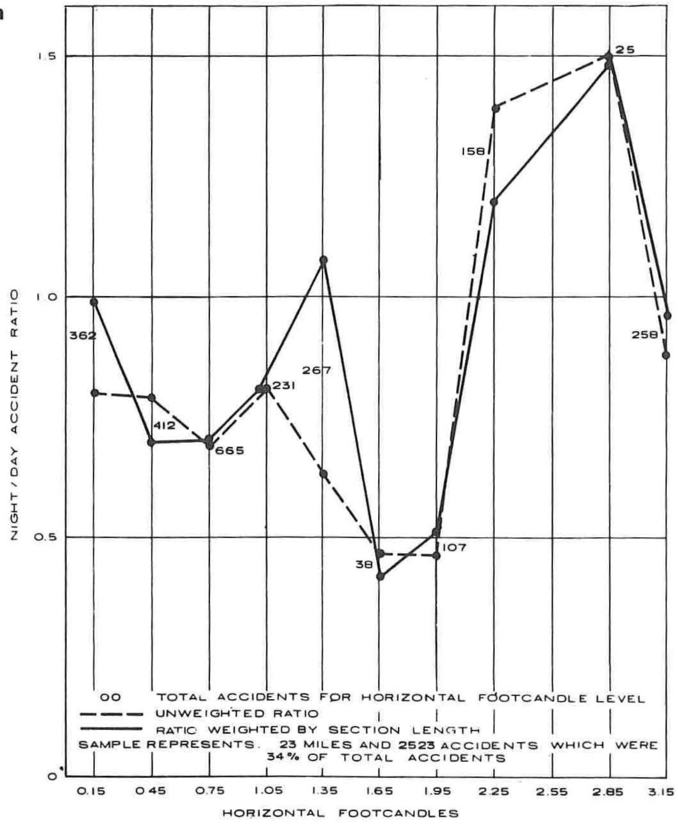


Figure 3. Relation between illumination level and accident experience for class 6 streets.

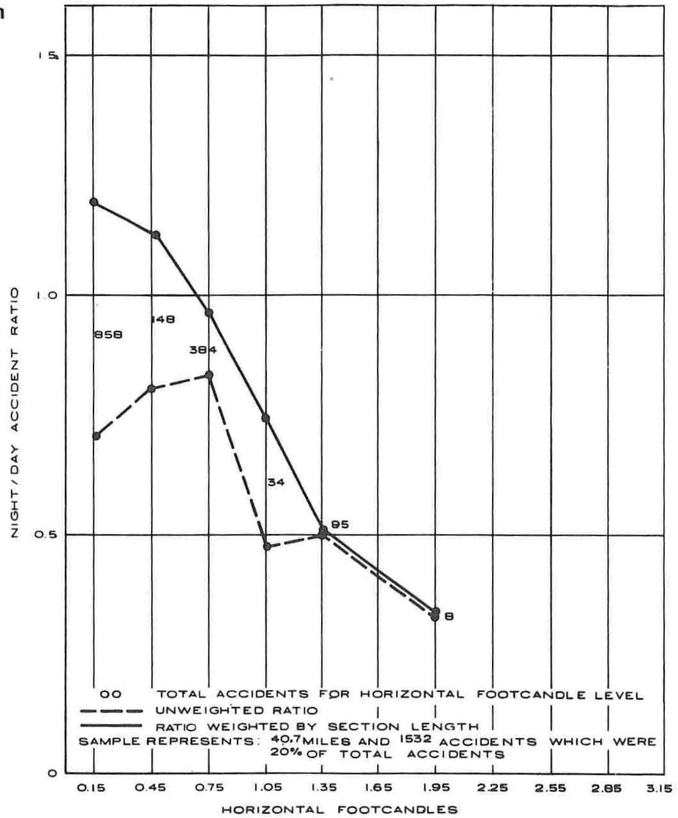


Figure 4. Relation between illumination level and accident experience for all street classes.

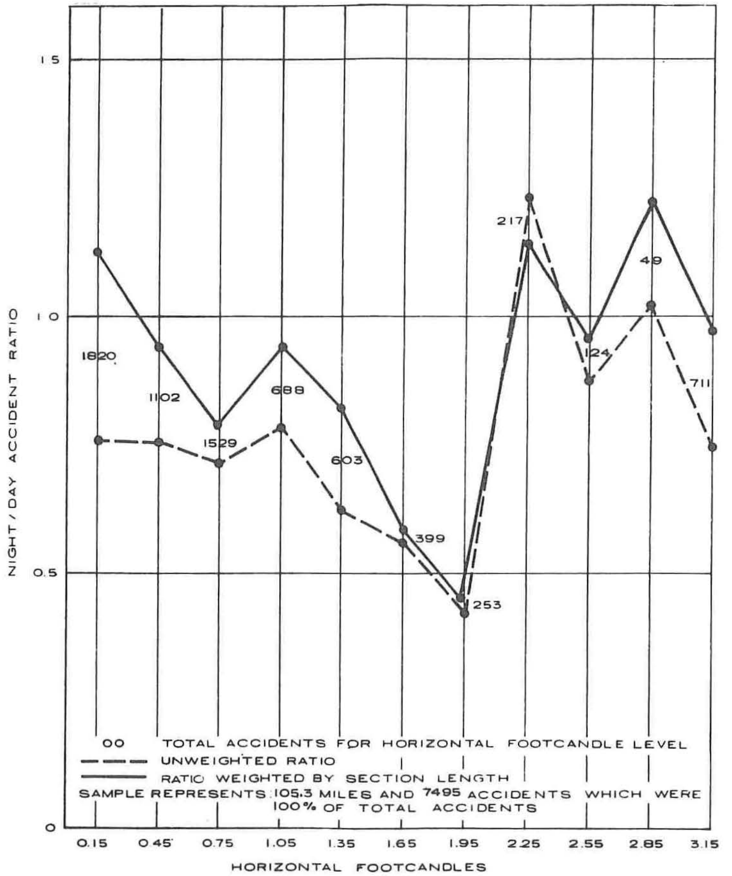


Table 3. Illumination levels that produce lowest night-day accident ratios.

Class	Accident Ratio	Illumination Level (HFC)	Specification (HFC)
1	0.38	1.05	2.0
2	0.46	1.8	1.2
3	0.62-0.54	0.75-1.6	0.9
4	0.36	0.75	1.2
5	0.36	1.05	0.9
6	0.47	1.05	0.6
Avg	0.42	1.95	

Table 4. Night-day accident ratios and optimum illumination levels.

Class	Data	Avg Accident Ratio	Low Accident Ratio	Optimum Illumination Level
1, 2	Raw[a]	0.71	0.42	1.95
	Weighted[b]	0.82	0.46	1.95
3[c]	Raw	0.84	0.71	0.75
	Weighted	1.00	0.62	0.75
4, 5, 6[d]	Raw	0.70	0.43	1.05
	Weighted	1.07	0.44	1.05

[a]Based on number of accidents.
[b]Weighted by section lengths.
[c]62 accidents at 1.65-HFC level not considered as valid low point.
[d]28 accidents at 1.95-HFC level not considered as valid low point.

For class 3 streets, the unweighted data on night-day accident costs showed a ratio of 1.5 at the optimum illumination level of 0.8 HFC. For collector streets, the data were not entirely consistent, but it appeared that an accident cost ratio of 1.0 would be appropriate when these routes were lighted to the optimum level of 1.0 HFC.

The total day accident costs for each range of maintained footcandles in each of the street classes can be multiplied directly by the night-day accident cost ratio. If the resulting value is then subtracted from the actual cost of nighttime accidents in each footcandle range, the difference will be the cost that might be saved by illumination of the route to the optimum values. Such calculations were made for each of the class groupings, and the potential accident cost savings are given in Table 5. Because of the uncertainties of the exact optimum or design illumination levels for each grouping, the potential cost savings were calculated only for those groups below the range in which the design level applied. Using this method of calculation and assuming that the routes had been lighted to the indicated levels, we estimated a potential savings of some \$4 million in accident costs for calendar year 1967.

Theoretically, accident costs would have been further reduced if some of the more brightly lighted routes had a lower level of illumination. However, data are not adequate to justify reducing existing lighting levels. More extensive studies might or might not produce such justification. Furthermore, the study was limited strictly to accident implication, without regard to other elements such as personal security or police needs.

The cost to provide the additional lighting to reach the design levels was estimated in order to develop benefit-cost ratios. In this step, lighting systems were designed and costs were estimated for a substantial number of individual sections for various street classifications. The added costs were calculated on a per mile basis by first subtracting the cost of existing lighting and then factoring the section length to a full mile. The average added cost for improvements in illumination for the various existing levels and street classes is given in Table 6. Also given are the mileages of each illumination group and the estimated annual cost to bring the lighting levels up to the assumed design values.

Direct benefit-cost ratios were calculated for each of the 3 combined classes of streets and are as follows:

Class	Ratio
1, 2	22:1
3	60:1
4, 5, 6	5:1

The greatest apparent benefit would lie in upgrading class 3. This is largely because the change in illumination would be the smallest of any of the classes and, hence, the added lighting cost would be minimal. Because of the statistical limitations, further study might indicate a somewhat different illumination level. If the desirable level were higher, it would reduce the benefit-cost ratio. Whatever adjustments are made, however, it appears that substantial benefits would be realized by upgrading lighting intensity on all of the major and collector streets.

SUMMARY OF FINDINGS

1. Streets with little or no illumination had substantially higher night-day accident ratios and accident cost ratios than the average for all streets in their respective groups. Inadequate lighting, therefore, contributes to accident hazards.

2. The type of street appears to be more of a factor in accident-illumination relations than is the type of abutting land use.

3. Streets with extremely high illumination levels tended to have night-day accident and accident cost ratios that were above the average for each group. It appears possible to "overlight" as well as to "underlight" a given street. However, data on several other important factors (such as streetlight glare, background storefront lighting, or sign lighting) were not evaluated.

Figure 5. Relation between illumination level and accident experience for class 1 and class 2 streets.

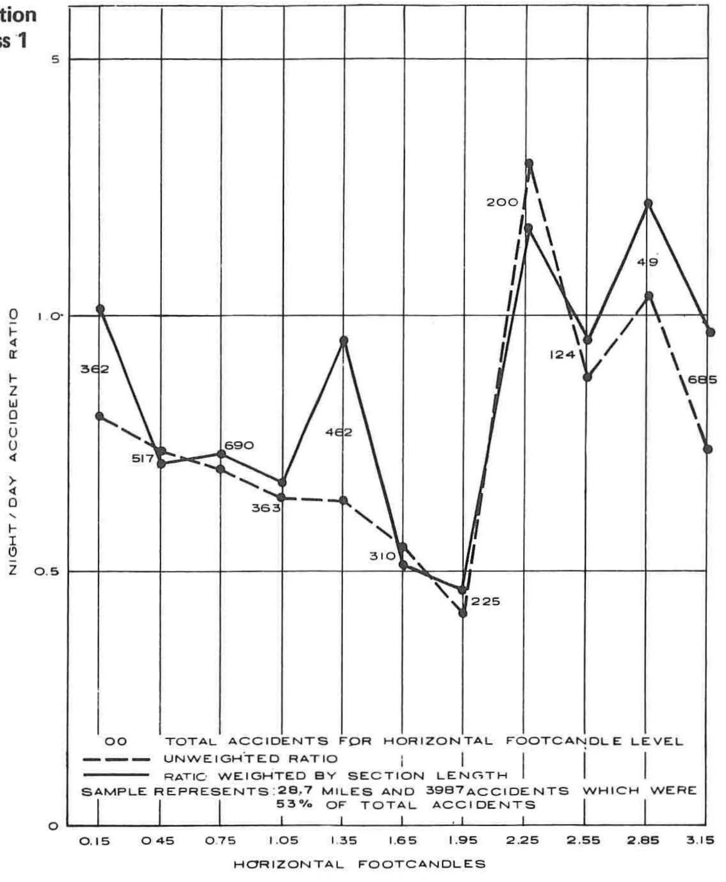


Table 5. Potential accident cost savings if streets are lighted to optimum levels.

Class	Night-Day Accident Cost Ratio[a]	Design Illumination Level (HFC)	Savings (millions of dollars) by Existing Illumination					
			0.00-0.29	0.30-0.59	0.60-0.89	0.90-1.19	1.20-1.50	Total
1, 2	0.8	1.8	0.470	0.729	0.258	0.135	0.243	1.835
3	1.5	1.5	0.930	0.680	—	—	—	1.610
4, 5, 6	1.0	1.0	0.337	0.199	0.058	—	—	0.594
Total			1.737	1.608	0.316	0.135	0.243	4.039

[a]Produced if existing illumination is upgraded to new design level.

Table 6. Costs of upgrading lighting.

Class	Illumination (HFC)	Sections		Added Cost/Mile[a] (dollars)	Miles			Annual Cost (dollars)
		Number	Percent		Number	Revised[b]	Upgraded	
1, 2	0.00-0.29	5	46	4,300	5.1	0	5.1	22,000
	0.30-0.59	8	50	5,100	5.5	0	5.5	28,000
	0.60-0.89	12	75	3,200	6.4	0	6.4	21,000
	0.90-1.19	5	56	3,400	2.9	0.3	2.6	9,000
	1.20-1.49	7	47	2,300	2.1	0	2.1	5,000
	Total							85,000
3	0.00-0.29	14	50	2,200	14.0	4.9	9.1	20,000
	0.30-0.59	8	44	1,100	7.7	1.2	6.5	7,000
	Total							27,000
4, 5, 6	0.00-0.29	17	20	3,800	28.0	0.4	27.6	105,000
	0.30-0.59	8	42	2,200	4.0	0	4.0	9,000
	0.60-0.89	14	48	1,200	10.8	0	10.8	13,000
	Total							127,000

[a]Average of sections checked. [b]Since 1967.

4. The apparent minimum (most favorable) night-day ratios of both number of accidents and accident costs were associated with the following illumination levels:

Class	Level (HFC)
1, 2	1.8
3	0.8
4, 5, 6	1.0

5. A substantial benefit-cost ratio would result if lighting on various street sections were upgraded to the values given above.
6. The methodology developed during the project is felt to represent a major contribution to the techniques of making such a study. The data were generally adequate to justify establishments of priority for systematically upgrading illumination of major and collector streets in Syracuse to minimize nighttime accidents and to maximize economic benefits.

ACKNOWLEDGMENT

This study was performed by De Leuw, Cather and Associates, Paul C. Box and Associates, and the Syracuse Department of Transportation. Assistance was rendered by Niagara Mohawk Power Corporation.

REFERENCES

1. American Standard Practice for Roadway Lighting. Illuminating Engineering Society, 1963.
2. Motor Vehicle Accident Costs. Wilbur Smith and Associates, 1966.

FREEWAY ACCIDENTS AND ILLUMINATION

Paul C. Box, Paul C. Box and Associates, Skokie, Illinois

The findings of a study of freeway accidents and illumination are reported. The time during which ambient light conditions are such that typical roadway illumination would have an effect was found to be from 15 min after sunset to 15 min before sunrise. Lighted freeways were found to have lower (better) night-day accident ratios than unlighted ones. The lighted freeways with the lowest illumination, averaging 0.6 horizontal footcandles maintained, had the best accident ratio. This corresponds to an initial illumination design level of about 1.0 HFC. A wide variation was found in average illumination between adjacent pairs of luminaires along specific freeway sections. This was found to be principally a result of differences in individual lamp output. The variations of HFC averages and uniformity are so great as to cast doubt on the real value of these elements in lighting design calculations.

•IN THE 1966 public lighting needs report to the U.S. Congress, data were presented from pilot studies of freeway accidents (1). Information was related to estimated vehicle-miles of travel, night-day accident ratios, illumination levels, and uniformity. Apparent trends were found in reduced night-day accident ratios (hence, actual reductions in accidents) with increased illumination and with improved uniformity. However, the illumination levels were calculated in-service values as reported by the responsible public agencies.

A study, undertaken in the Illuminating Engineering Research Institute, was designed to expand the data base and to attempt definition of optimum illumination levels and uniformities from the standpoint of accident reduction. In the execution of the study. careful attention was given to tabulation of accidents from the reports themselves (to eliminate computer data errors) and to collection of traffic volume counts. The attempt was made to include a wide variety of urban and suburban freeway conditions, such as number of lanes, traffic volumes, and illumination levels and uniformities, including no illumination.

Data were gathered from metropolitan areas of Toronto, Chicago, Atlanta, Dallas, Phoenix, and Denver. There were 203 miles of routes and more than 21,000 accidents included in the summary. Items tabulated from each accident report included time of accident and weather condition, accident severity, type of accident, portion of freeway roadway on which the accident occurred (main line, ramp exit from main line, ramp entrance to main line, and entirely within the ramp itself), and age of the driver who struck another object or who ran off the road (not necessarily the driver who was legally responsible for the accident).

Figure 1 shows the card used to code the accident data, and Table 1 gives a summary listing of all routes that were studied.

From the standpoint of tabulation, a location type of accident file is highly desirable. The tabulation of accident data from copies of the police report can be time-consuming, but it appears to be a necessary control. The number of accidents directly relatable to freeway illumination was found to vary widely in the check between actual tabulations and data processing printouts. In a check of 3 systems, differences of 19 to 62 percent were found.

DAY-NIGHT THRESHOLD POINT

An important initial step in the project was to find a method of accurately relating freeway accidents and traffic volumes to illumination. This, in part, required

Figure 1. Accident coding card.

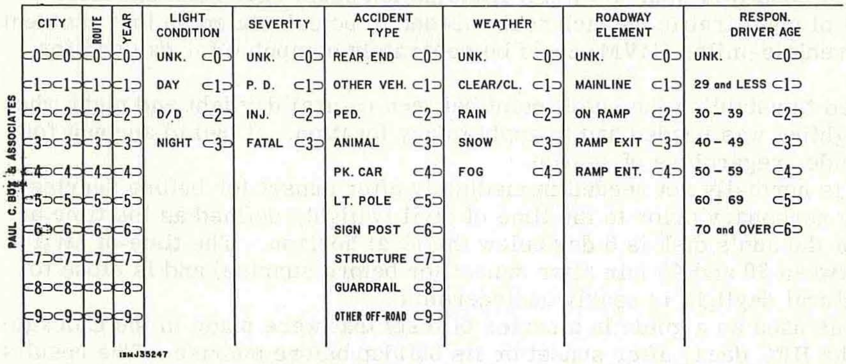


Table 1. Summary of route data.

Route	Length (miles)	Data Years	Accidents Day	Accidents Night	Accidents Total	Million Vehicle-Miles	Accidents/MVM Day	Accidents/MVM Night	Accidents/MVM Total	Night-Day Ratio	Area	Lighting
4 Lanes												
I-85, DeKalb County	8.8	64-67	888	356	1,244	523	2.29	2.63	2.38	1.15:1	Suburban	No
I-85, Atlanta	3.4	64-67	2,184	697	2,881	356	8.32	7.49	8.11	0.90:1	Urban	Yes
I-75, Atlanta	3.8	64-67	989	266	1,255	276	4.82	3.75	4.54	0.82:1	Urban	Yes
401 Toronto	43.0	64-66	570	466	1,036	945	0.81	1.89	1.10	2.33:1	Rural	No
400 Toronto	40.6	64-66	484	347	831	617	1.06	2.17	1.34	2.05:1	Rural	No
I-25, Denver	5.0	65-66	120	75	195	130	1.20	2.50	1.50	2.08:1	Suburban	Yes
N. C. sec. 1, Dallas	3.3	65-67	438	182	620	193	2.98	3.96	3.20	1.31:1	Suburban	Yes
N. C. sec. 2, Dallas	2.2	65-67	599	140	739	150	5.20	3.88	4.92	0.73:1	Urban	Yes
Ill-394 sec. 8, Chicago	3.5	65-68	83	77	160	unk.	unk.	unk.	unk.	2.80:1	Suburban	No
Ill-394 sec. 9, Chicago	1.5	65-68	22	21	43	unk.	unk.	unk.	unk.	2.90:1	Suburban	No
6 Lanes												
Q. E. W., Toronto	5.5	63-65	417	240	657	237	2.74	3.88	2.77	1.42:1	Urban	Yes
I-25, Denver	7.0	65-66	514	249	763	150	4.47	7.11	5.08	1.59:1	Urban	Yes
M-39, Detroit	8.0	65-66	484	334	818	unk.	unk.	unk.	unk.	2.07:1	Urban	Yes
I-17, Phoenix	6.3	63-66	410	207	617	320	1.68	2.69	1.93	1.63:1	Urban	Yes
N. C. sec. 3, Dallas	1.9	65-67	716	180	896	159	5.90	4.80	5.63	0.81:1	Urban	Yes
I-75/85, Atlanta	2.0	65-67	1,182	459	1,641	174	9.24	9.98	9.44	1.08:1	Urban	Yes
I-20 sec. 7, Atlanta	2.8	64-67	407	205	612	214	2.55	3.73	2.86	1.46:1	Urban	Yes
I-20 sec. 6, Atlanta	1.0	66-67	198	59	257	51	5.10	4.40	4.91	0.87:1	Urban	Yes
I-294 sec. 2, 6, Chicago	9.8	60-67	428	270	698	976	0.59	1.06	0.72	1.80:1	Suburban	No
I-294 sec. 0, 5, Chicago	4.4	60-67	126	71	197	439	0.39	0.62	0.45	1.59:1	Suburban	Partial
I-294 sec. 3, Chicago	1.7	60-67	52	40	92	127	0.55	1.21	0.73	2.20:1	Suburban	Yes
I-294 sec. 1, 4, Chicago	0.8	60-67	192	72	264	75	3.50	3.60	3.51	1.02:1	Suburban	Yes
I-55 sec. 1-4, Chicago	2.7	65, 66, 68	286	167	453	unk.	unk.	unk.	unk.	1.90:1	Urban	Yes
I-55 sec. 0, 7-9, Chicago	7.2	65, 66, 68	210	166	376	unk.	unk.	unk.	unk.	2.40:1	Urban	Yes
I-55 sec. 5, Chicago	2.3	65, 66, 68	135	80	215	unk.	unk.	unk.	unk.	1.80:1	Urban	Yes
I-55 sec. 6, Chicago	4.0	65,66, 68	287	144	431	unk.	unk.	unk.	unk.	1.50:1	Urban	Yes
I-94 sec. 2, Chicago	1.5	65-68	124	159	283	unk.	unk.	unk.	unk.	3.80:1	Urban	Yes
I-94 sec. 1, Chicago	1.2	65-68	243	184	427	unk.	unk.	unk.	unk.	2.70:1	Urban	Yes
I-94 sec. 3, Chicago	0.5	65-68	156	96	252	unk.	unk.	unk.	unk.	1.80:1	Urban	Yes
I-94 sec. 0, 4, Chicago	2.1	65-66	89	91	180	113	1.06	3.19	1.59	3.00:1	Urban	No (before)
I-94 sec. 0, 4, Chicago	–	68	58	27	85	66	1.18	1.59	1.29	1.30:1	Urban	Yes (after)
I-94 sec. 5-7, Chicago	3.2	65-66	105	105	210	153	0.93	2.72	1.37	2.90:1	Urban	No (before)
I-94 sec. 5-7, Chicago	–	68	79	53	132	86	1.22	2.45	1.53	2.00:1	Urban	Yes (after)
8 and 10 Lanes												
I-75/85, Atlanta	1.1	66-67	434	131	565	90	6.48	5.70	6.29	0.88:1	Urban	Yes
401, Toronto	2.6	66	180	97	277	96	2.54	3.88	2.93	1.53:1	Urban	Yes
I-20, Dallas	4.6	66-67	258	93	351	217	1.61	1.65	1.61	1.01:1	Urban	Yes
I-35, Dallas	4.2	66-67	512	186	698	275	2.43	2.83	2.52	1.15:1	Urban	Yes
Total	203.5				21,439	7,131+						

determination of whether specific accidents coded as occurring at dusk or dawn happened during a night condition when artificial illumination could have been of value. The actual amount of night traffic on each route needed to be calculated so that accident rates per million vehicle-miles (MVM) could be separately computed for day and for night travel.

The method used to establish the cutoff point between natural daylight and night when artificial street lighting was needed had to apply to any location. It had to account for latitude and longitude, regardless of season.

Artificial light is normally not needed immediately after sunset (or before sunrise). It becomes clearly necessary prior to the time of civil twilight, defined as the time at which the center of the sun's disk is 6 deg below the local horizon. The time of civil twilight occurs between 30 and 40 min after sunset (or before sunrise) and is close to the point where natural daylight is nearly undiscernible.

Civil twilight was used as a guide in a series of tests that were made in the Chicago area to measure the HFC decay after sunset or its buildup before sunrise. The results of part of the twilight measurements are shown in Figure 2. This shows the change in ambient illumination after sunset in January, April, and July. These times represent the 3 near-extreme conditions of sunrise and sunset daylight rate of change. In the threshold area, the curves are separated by only about 2 min.

For lighting purposes, it was assumed that the threshold point lay midway between sunset-sunrise and civil twilight. This point was originally estimated by visual checks. Figure 2 shows ambient values of 1.5 to 4.9 HFC at this point. A change of only 6 min ($^1/_{10}$ hour) produces a drop to a level of 1 or 2 footcandles for even the higher value. In this immediate area then, a point of ambient illumination is reached when artificial lighting levels typically used on roadways (0.5 to 1.5 HFC) represent a significant added factor in driver visibility.

The same results were found for a sunrise condition, with even less difference among the seasonal light change values. The range in ambient illumination at the "assumed dark" point was 0.9 to 3.3 HFC.

A close approximation of the threshold point occurs 15 min before sunrise and 15 min after sunset. Checks were made with moderate to heavy cloud cover, but only about a 5-min variation was found in the basic assumed dark threshold point.

Estimates were also made on extremely cloudy days with precipitation. Variation in threshold time was found to be only about 10 to 15 min. Because relatively few days of the year have this extreme condition, it was felt this should not make a significant difference. Accident reports seldom reflect the time of an accident closer than 5 min. Traffic volumes are not perfectly spread during each minute of the threshold hours.

NIGHT TRAFFIC

From the volume studies, on an hour-by-hour basis, the finding was made that 25 percent of urban freeway traffic consistently moves at night. Latitude, longitude, local DST practice, and metropolitan area size appear to cause no significant variation.

This is an important finding, for it allows direct calculation of rate ratios in the absence of traffic counts. The night-day ratio (per million vehicle-miles or any other travel exposure measure) is mathematically equal to 3 times the number of night accidents divided by the number of day accidents.

LIGHTING MEASUREMENTS AND VARIATIONS

Most measurements of existing lighting were taken under "live" traffic conditions between 2:00 and 5:00 a.m. Measurements were made at 14 freeway locations. These were chosen to be as representative as possible of typical spacing for each route. Readings at 10 sites were taken directly below 2 to 7 adjacent luminaires. For each location these "below-luminaire" HFC readings were tabulated and averaged. Grid readings were then taken between the pair of luminaires that best represented an average. Points were chosen along pavement edges and at quarter-spacing transverse lines.

From the grid readings, typical in-service illumination and uniformity ratios were determined. The initial design values were calculated from manufacturers' photometric

curves. Lamp correction factors were applied, based on the types of lamps actually in use at the time of measurement. Measured and calculated data were then compared to produce typical examples of in-service depreciation.

Comparison of the point-by-point grid measurements with calculated initial design data for the 10 locations showed light losses ranging from 18 to 72 percent. The average was 49 percent for an average system age of nearly 8 years. Depreciation for installations as old as 7 years averaged 47 percent, and systems 8 to 15 years old averaged 54 percent.

All of the below-luminaire readings in 10 sections were compared with calculated initial illumination for this point, and depreciations of 35 to 73 percent were found. The overall average light loss was 51 percent, as measured by this rough approximation method, which thus compared favorably with the 49 percent average from the grids.

In-service uniformity ratios (average-to-minimum) found in the grid measurements were worse than the calculated initial values in all but 2 cases. The average change was 58 percent for those that became worse. At one location where grid readings were made, the nearby contributing luminaires were cleaned and new grid readings taken. The direct effect of this cleaning was to increase the average illumination from 0.45 to 0.50 HFC (an increase of 10 percent). However, the cleaning worsened the average-to-minimum uniformity ratio, from 9:1 before to 10:1 after.

The first 10 test sections involved practices of burnout replacement of lamps rather than group replacement. In practically all of these cases, the only luminaire cleaning performed was at the time of lamp replacement (or pole knockdown). In fairness to the cooperating agencies in this study, it should be reported that several were beginning programs of improved maintenance.

Depreciation factors were also compared at 4 locations of equal age (4.5 to 4.7 years). Two systems had burnout replacement and luminaire washing only at burnout, and the other 2 had group replacement at 16,000 hours (about every 4 years) plus annual washing. An average depreciation of 54 percent was found for the poor maintenance systems versus only 36 percent for the group maintenance. This offers evidence in favor of group replacement programs, which are endorsed by most engineers. However, depreciation in uniformity ratio was just as bad under one maintenance system as another.

The city of Philadelphia requires its maintenance contractor to regularly test mercury lamps removed from service during group replacement programs. The testing involves comparison against "standard" lamps, and data are tabulated on the percentage of lumen output of the lamp being tested. The date of lamp installation is placed on the base, and the date of removal is known. It is, therefore, possible to compare months in service with lumen output (expressed as percentage of a 100 percent standard).

Data from 804 such tests were secured from the contractor. Findings are given in Table 2. Wide variations can appear early in lamp service. Most group replacement is performed at a 3- to 4-year lamp life. The extremes in output of 40 to 94 percent, as compared with the 78 percent average for this length of life, are equivalent to a range of -49 to +21 percent of the average. The range for all lamp ages, as compared with the 67 percent overall average, is an example of what might be expected in the field under a burnout replacement program; this variation was -52 to +33 percent.

These laboratory findings were compared with the below-luminaire readings from each freeway route section. The field readings were expressed as a percentage of the average of the 2 lamps at the "typical" test locations. This was done separately for each of the 8 routes so the problem of different types of luminaires would be eliminated. The extreme reading variations were then averaged. The limits thus found ranged from a low of -49 percent to a high of +66 percent for the routes with burnout replacement systems. The range was -40 to +69 percent for the group replacement routes.

The field data show an excellent fit with the laboratory findings on the low end of the scale but a poor fit on the upper end. They are sufficiently in agreement, however, to sustain the hypothesis that freeway illumination usually varies about 50 percent on either side of any "nominal" value measured in the field.

The ±50 percent variation occurs under ideal conditions of constant geometry and spacing to mounting height ratios. When the actual spacing and variable-roadway width differences (such as those that occur at ramp entry or exit points) are considered, an even wider range exists in the hypothetical "average" HFC.

The foregoing findings in actual roadway illumination show such extremes in HFC averages and uniformity (average-to-minimum) that serious doubt is cast on the value of such elements in lighting design. The erratic performance of systems certainly invalidates any analysis of fine differences among various designs. The subject research assignment was to investigate relatively small differences in lighting and to search for nominal design values. However, the extent of variations may be enough to "wash out" meaningful analysis. For example, a variation of 50 percent produces in an 0.8-HFC nominal system a range from 0.4 to 1.2 in area averages at random locations. Another system with doubled nominal illumination of 1.6 HFC will vary from 0.8 to 2.4. This obviously overlaps well into the first system.

In order to achieve reasonable separation, a threefold difference appears to be needed in nominal level (such as 0.6 versus 1.8 HFC). Extremes of this magnitude were generally not located for study in the subject research.

LIGHTED VERSUS UNLIGHTED ROUTES

As a group, the lighted freeways for which data are given in Table 1 had an average night-day ratio of 1.43 for all types of accidents. The unlighted freeway average was 2.37. If a freeway experiences 1,000 day accidents during any time period, the expected number of night accidents can be calculated for any assumed night-day rate ratio. The lighted average ratio of 1.43 produces 475 night accidents by use of the equation $E_N = R\ A_D/3$, where E_N = expected number of night accidents, R = night-day rate ratio, and A_D = number of day accidents.

The unlighted average ratio of 2.37 produces 790 night accidents. The difference is 315, which represents 40 percent fewer night accidents. If compared with the 1,790 total of day and night accidents, the average overall reduction would be 18 percent.

This example indicates that the illumination of an unlighted urban freeway could theoretically reduce night accidents by an average of 40 percent or overall accidents by 18 percent.

If only the fatal and injury accidents are considered, the night-day ratio is 1.69 for lighted freeways and 3.53 for unlighted ones. A lighted freeway with 1,000 fatal and injury accidents during the day would average 560 such accidents at night. If unlighted, however, there would be 1,180 such night accidents. The apparent effect of lighting on the fatal and injury accidents is a reduction of 52 percent in night accidents.

The statistical analysis involved a chi-square test for association between accident rate ratios and the presence or absence of lighting. A total of 59 observations were available, 18 of which involved unlighted route sections. (An "observation" is 1 year of data from 1 section. Thus, 1 route with 3 years of data produces 3 observations.) The data were entirely adequate to allow the test to be performed. The test established that lighted freeways as a group have lower rate ratios for all types of accidents than unlighted freeways. A highly significant (1 percent) value of chi-square was found. This means that less than 1 possibility in 100 exists for a chance occurrence. Testing of only the fatal and injury accidents resulted in a similar finding that was significant at the 5 percent level (less than 5 possibilities in 100 exist for a finding due to chance alone).

BEFORE-AND-AFTER STUDY

In the Chicago area, an opportunity was found to compare accidents before and after relighting 5.3 miles of 6-lane urban freeway. Unfortunately, resurfacing and minor reconstruction along the route were commenced about 1 year after installation of the lighting. The after period of study was thus limited to only 1 year. Data were available for 2 years in the before period, however.

The study route was Interstate 94 between 132nd Street and 167th Street. This route had a narrow median (12 ft) between 132nd Street and 146th Street. In the rest of the lighted section, the median width was 33 ft.

Study findings from each section are given in Table 3. A direct reduction occurred during the after period in all types of accidents. A large change in the number of accidents per MVM is also found. However, the total number of accidents is less than 600 for all 3 years of data from both sections.

Figure 2. Seasonal effect of ambient illumination.

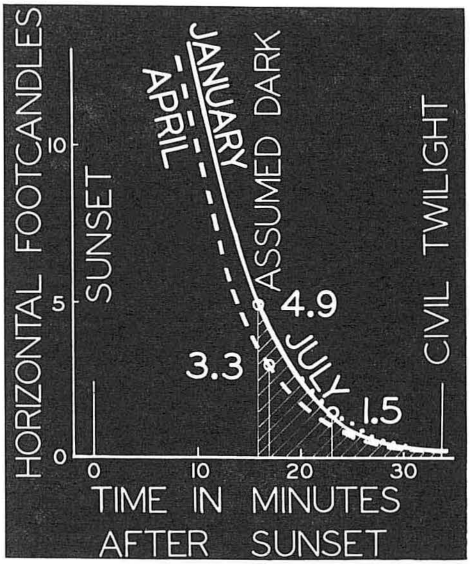


Table 2. Lamp output as function of service.

Months in Service	Number Tested	Percentage of Standard Lamp		
		Low	High	Average
Under 24	15	54	98	79
24 to 35	70	46	94	75
36 to 47	83	40	94	78
48 to 59	171	30	94	70
60 to 71	210	16	88	66
72 to 83	126	20	90	65
84 to 95	113	18	84	53
Over 95	24	30	74	50
Total	804	32	89	67
Variation from avg		-52	+33	

Table 3. Results of before-and-after lighting study.

Freeway Location	Time	Before					·After				
		All Accidents			Injury-Fatal Accidents		All Accidents			Injury-Fatal Accidents	
		Num-ber	Per-cent	Per MVM	Num-ber	Per-cent	Num-ber	Per-cent	Per MVM	Num-ber	Per-cent
132nd to 146th	Day	40	47	1.06	15	39	29.	68	1.18	17	63
	Night	46	53	3.19	23	61	14	32	1.59	10	37
	Total	86	100	1.59	38	100	43	100	1.29	27	100
146th to 167th	Day	105	51	0.93	30	37	79	60	1.22	30	60
	Night	105	49	2.72	52	63	53	40	2.45	20	40
	Total	210	100	1.37	82	100	132	100	1.53	50	100

The night-day accident ratios were as follows:

Location	Before	After
132nd to 146th	3.0:1	1.3:1
146th to 167th	2.9:1	2.0:1

The chi-square test was applied to the night-day ratios. The probability of the difference in rates being due to chance occurrence was found to be less than 1 in 100 (a chi-square value significant at 1 percent). This result suggests that the accident rate ratio is significantly lower after lighting was installed. However, the data consist of only 12 observations, which does not fulfill the generally accepted requirements of at least 20 observations for a 2 by 2 chi-square contingency test (each cell should have an expected value of at least 5). Hence, the result of this test must be treated with some caution.

As a second statistical test, it was assumed that any trend in day accident figures would also be representative of any trend in night accidents. From the day values for the 2 study sections, a trend was established during the period covering both the before and the after conditions. This trend was applied to the before night figures to obtain the expected number of accidents during the after period, if lighting had not been installed. A t-test was then performed on the difference between this expected figure and the actual figure after installation of lighting. The t-value for both sections together was significant at the 10 percent level. For the north section only, a t-value of 5 percent was found.

These tests indicate that the installation of lighting quite possibly lowered the night accident rate, but an exhaustive statistical confirmation is lacking.

LIGHTED VERSUS UNLIGHTED SECTIONS OF SAME ROUTE

Interstate 85 in Atlanta is lighted, but its extension in DeKalb County is unlighted. Direct comparison studies were performed in which 2 years of data from the lighted section and 4 years from the unlighted section were used.

The lighted portion is 3.4 miles in length and extends northeast from a major interchange point. The basic design consists of two 24-ft roadways with a 14-ft median. There are 4 interchanges along this section, in addition to the main freeway junction. The junction is of a directional type, and the interchanges are essentially of the diamond type. During the 1966 and 1967 study period, the route experienced 189 MVMT. Fixed lighting utilizes a 28-ft mounting height, type 3 distribution, 6-ft overhang, and 120-ft staggered spacing. Measurements taken at an interchange location on the route during 1967 showed a maintained illumination level of 0.38 HFC and a uniformity ratio of 2.7 to 1. However, subsequent measurements in a location more typical of the overall route average found a level of 0.33 HFC and a uniformity ratio of 16 to 1.

The unlighted section is 8.8 miles in length and is generally similar to the lighted portion except for a wider median and lower traffic volume. The section has 7 interchanges, generally of the diamond type. One is a major interchange with a partially completed circumferential freeway loop. During the 1963 to 1967 study period, the unlighted section had 523 MVMT.

The relation of the number of accidents, roadway elements, and day or night conditions is given in Table 4. The accidents have been grouped into the following types:

Accident	Type
Rear end	1
Other vehicular	2
Pedestrian and parked car	3
Fixed object and other off-road	4

The day and night accidents/MVM and the night-day ratios are also given in Table 4. (Ratios are omitted where only small accident sample sizes were available.) A substantial difference in direct accident rates exists between the 2 sections. It is, therefore, necessary to relate these rates on a ratio basis. The ratios for the unlighted route are higher for type 1 than for type 2 accidents. Conversely, the ratio for type 3

accidents is higher for the lighted section. (A larger night-day ratio indicates a correspondingly more hazardous night condition.) Certain accident types and roadway elements predominate as the percentages given at the bottom of Table 4 show.

These data show that certain apparently dangerous locations actually had relatively few accidents. Such locations include the exit ramp, or gore position, and the ramps themselves. Type 4 accidents at these locations accounted for only 1 percent of the accidents on the lighted section and 2 percent on the unlighted section.

Primary accident problems in the study sections involve rear-end collisions. The high concentration of such accidents at ramp entrances can be partially traced to lack of adequate acceleration lanes. The unlighted section had better designs in this respect.

INTERCHANGE LIGHTING

In several route sections, accidents were tabulated separately in the interchange areas (between extreme ends of exiting and entering ramp tapers) and areas between the interchanges. The percentage of night accidents occurring within each grouping was chosen as the best means of comparison. Summary data are given in Table 5. In most of the cases, a higher percentage of accidents occurred at night between the interchanges. This appears to be a characteristic that is not changed by lighting. The before-and-after sections show an even more pronounced difference after lighting was installed. A check was made of 5 freeway sections having 4,000 accidents. From 29 to 79 percent of all the section accidents occurred between interchanges. The average for all 5 sections was 50 percent. Data such as these should generate careful review of policies that favor interchange lighting over continuous lighting.

LIGHT-POLE COLLISIONS

Most of the lighted routes studied had relatively standard mounting heights of 28 to 33 ft. Thus, the better illuminated routes had closer pole spacing. One 4-lane section with a measured HFC average of 0.50 had 35 poles/mile, and an adjacent section of the same 4-lane route with a 1.1 HFC had 66 poles/mile. The lower lighted route had 739 total accidents, 8 of which (1.1 percent) involved light poles as a first significant object struck. The total exposure (poles/mile × MVM) was 5,250 MV, or 655 MV/pole accident.

The higher lighted route had 620 accidents, 17 of which involved light poles (2.7 percent). Thus, an increase of 90 percent in the number of poles/mile also numerically increased the number of pole accidents by 90 percent. The pole percentage of total accidents was $2\frac{1}{2}$ times as great. The exposure was 12,700 MV for the higher lighted route, which is also $2\frac{1}{2}$ times that of the lower lighted route. The route had 1 pole accident/745 MV.

A third route checked had 8 lanes, 0.9-HFC illumination, and 80 poles/mile. This route had 698 accidents during the study period; 27 (3.9 percent) involved light poles. The total exposure was 22,000 MV or 815 MV/pole accident.

On a vehicle mileage basis, 2 lower lighted routes experienced rates of 0.05 and 0.06 pole accidents/MVM. The 2 better lighted route rates were 0.09 and 0.10/MVM. Thus, doubling the number of poles increased the actual number of pole accidents and tended to double the accident mileage rate involving poles.

EFFECT OF ILLUMINATION LEVEL

The routes selected for study have a wide range in accident rates. These vary from a low of 0.39 to a high of 9.24/MVM during the day. At night, the range is 0.62 to 9.98/MVM. The average overall rate (for the routes with volume data) is 3.25/MVM.

From the standpoint of testing a broad range of different conditions of congestion, geometric design, climate, and metropolitan area size, the variety of route sections is highly desirable. The magnitude of differences, however, clearly precludes any direct comparison of accident rates, and analysis of lighting effect required use of the night-day ratio of rates.

During the early part of this research, it was still assumed that field measurements on a sampling basis would provide a narrow range of factors, which could be used to relate calculated and actual field lighting levels and uniformities. It was assumed that

Table 4. Summary of accidents in I-85 study.

Item	Lighted Section				Unlighted Section			
	Type 1	Type 2	Type 3	Type 4	Type 1	Type 2	Type 3	Type 4
Number of Day Accidents								
Main line	284	93	3	88	306	110	7	123
Ramp entrance	574	25	1	2	301	24	1	0
Ramp exit	2	4	0	1	6	6	1	6
On-ramp	3	1	0	1	1	2	2	3
Total	863	123	4	92	614	142	11	132
Number of Night Accidents								
Main line	77	30	10	90	90	61	9	90
Ramp entrance	119	14	0	4	83	3	0	1
Ramp exit	2	4	0	6	3	5	1	9
On-ramp	0	0	1	2	C	0	1	2
Total	198	48	11	102	176	69	11	102
Night-Day Ratio								
Main line	0.79	0.92	—	2.92	0.83	1.61	—	2.00
Ramp entrance	0.59	—	—	—	0.78	—	—	—
Ramp exit and on-ramp	—	—	—	—	—	—	—	—
Overall	0.65	1.11	—	3.16	0.82	1.41	—	2.23
Accidents/MVM								
Day	6.15	0.88	—	0.66	1.58	0.36	—	0.34
Night	4.02	0.98	—	2.08	1.30	0.51	—	0.76
Percentage of Section Accidents								
Main line	25	9	12	1	31	14	17	1
Ramp entrance	48	3	—	—	30	2	—	—
Ramp exit and on-ramp	—	1	1	—	1	1	2	1
Total	73	13	13	1	62	17	19	2

Table 5. Percentage of night accidents within and between interchanges.

Route	Type of Interchange	Unlighted		Lighted	
		Within	Between	Within	Between
I-85, DeKalb County		25	33	—	—
I-94 sec. 3, Chicago	Cloverleaf	—	—	38	—
I-94 sec. 1-2, Chicago	Diamond	—	—	43	56
I-94 sec. 0, 4, Chicago	Cloverleaf	46[a]	52[a]	25[b]	34[b]
I-94 sec. 5-7, Chicago	Cloverleaf	49[a]	52[a]	36[b]	43[b]
Ill-394 sec. 8-9, Chicago	Cloverleaf	49	48	—	—
I-55 sec. 0-4, 7-9, Chicago	Cloverleaf	—	—	42	38
I-55 sec. 5-6, Chicago	Diamond	—	—	33	37

[a]Before. [b]After.

Table 6. Illumination of urban and suburban route sections.

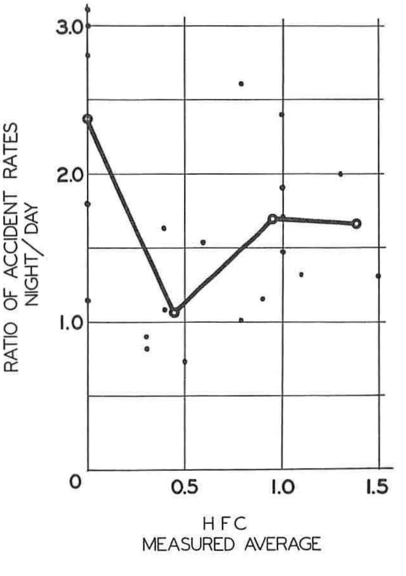
Route	Accidents/ MVM Day	Accidents/ MVM Night	Night-Day Ratio	Illumination HFC	Illumination Uniformity
4 Lanes					
I-85, DeKalb County	2.29	2.63	1.15:1	0	—
I-85, Atlanta	8.32	7.49	0.90:1	0.3	16.0:1
I-75, Atlanta	4.82	3.75	0.82:1	0.3	16.0:1
N. C. sec. 1, Dallas	2.98	3.96	1.31:1	1.1	3.2:1
N. C. sec. 2, Dallas	5.20	3.88	0.73:1	0.5	3.6:1
Ill-394 sec. 8-9, Chicago	—[a]	—[a]	2.80:1	0	—
6 Lanes					
I-17, Phoenix	1.68	2.69	1.63:1	0.4	15.0:1
N. C. sec. 3, Dallas	5.90	4.80	0.81:1	0.3	7.5:1
I-75-85, Atlanta	9.24	9.98	1.08:1	0.4	4.0:1
I-20 sec. 7, Atlanta	2.55	3.73	1.46:1	1.0	20.0:1
I-294 sec. 2, 6, Chicago	0.59	1.06	1.80:1	0	—
I-55 sec. 1-4, Chicago	—[a]	—[a]	1.90:1	1.0	3.7:1
I-55 sec. 0, 7-9, Chicago	—[a]	—[a]	2.40:1	1.0	2.5:1
I-55 sec. 5-6, Chicago	—[a]	—[a]	1.70:1	1.0	—[b]
I-94 sec. 1-3, Chicago	—[a]	—[a]	2.60:1	0.8	2.7:1
I-94 sec. 0, 4, Chicago	1.06	3.19	3.00:1	0	—
I-94 sec. 0, 4, Chicago[c]	1.18	1.59	1.30:1	1.5	4.5:1
I-94 sec. 5-7, Chicago	0.93	2.62	2.90:1	0	—
I-94 sec. 5-7, Chicago[c]	1.22	2.45	2.00:1	1.3	4.0:1
8 and 10 Lanes					
I-20 sec. 4, Dallas	1.61	1.65	1.01:1	0.8	3.5:1
I-35 sec. 7, Dallas	2.43	2.83	1.15:1	0.9	5.1:1
401 Toronto[d]	2.54	3.88	1.53:1	0.6	1.8:1

[a]Insufficient traffic counts to establish MVM rate. Ratio calculated from night percentage.
[b]Two sections with differing uniformities, combined.
[c]After lighting.
[d]Not used in statistical tests.

Table 7. Relation between illumination and night-day accident ratio.

Illumination (HFC)	Number of Samples	Night-Day Accident Ratio All	Night-Day Accident Ratio Injury-Fatal
Lighted			
0.3 to 0.6	7	1.07	1.40
0.8 to 1.1	8	1.69	1.93
1.3 to 1.5	2	1.65	1.85
Avg	17	1.43	1.69
Unlighted	5	2.37	3.53

Figure 3. Accident ratios and average illumination.



the summary data would be usable from 14,000 Chicago and Detroit accidents, as gathered in the public lighting needs study. When a correlation between calculated and measured values was not found, it was decided to not use any accident data from lighted routes, unless field measurements were available.

Twenty-two route sections were usable for the basic illumination analysis. These are given in Table 6. The day and night accident rates, the night-day ratios of these rates, and the results of illumination measurements are also given.

Table 7 gives a comparison of lighted and unlighted groups. Rate ratios are given for all accidents and for only fatal and injury accidents. Rates for all accidents are shown in Figure 3. The sections with a lighting level between 0.3 to 0.6 HFC had the best ratio of night-day accident rates. A chi-square test established that this group had a very significantly lower ratio (the probability of this being a chance finding is less than 1 in 1,000). Testing of only fatal and injury accidents resulted in a similar finding. The sections with higher illumination values appear to level off at an average ratio between 1.6 and 1.7. The higher illumination group was tested against the unlighted group, and no significant difference was found. The chi-square values, however, suggest that there is a utility in the higher illuminated freeways, as compared with unlighted ones, even though the data did not allow significant differences to be established.

The data do not allow specification of the optimum illumination level from the standpoint of accident reduction. No study sections were available with higher illumination such as 2.0 or 2.5 HFC. The findings do not imply that such higher levels have utility, nor do they disprove the possibility.

If a relation exists between uniformity (either average or maximum to minimum), it was not identified in the research. The failure to find any relation is understandable in view of the illumination variations found along the subject routes.

EFFECT OF LATITUDE

The northern area routes tended to have high illumination values, and the southern routes had mixes of high and low levels. The southern locations were, therefore, examined separately. As a group, the lighted routes showed a better accident rate ratio than the unlighted (DeKalb County, Georgia) route. Also, those lighted sections with lower illumination had significantly better ratios than the lighted sections with higher levels. Thus, the presence of a geographic bias on the illumination levels has no apparent effect on the overall statistical findings based on data from both north and south locations.

COST-BENEFIT ANALYSIS

For the urban data as a whole, the average annual number of day accidents ranged from 12 to 160 per mile of 4-lane lighted freeway, with an average of 74. For 6-lane routes the range was 4 to 295, with an average of 52; for 8- and 10-lane routes, the range was 28 to 197, with an average of 89. These values have been used to compute the expected number of average night accidents for urban freeways with and without lighting. The average accident costs have been compared with estimated typical freeway lighting costs, including installation plus 20-year maintenance and energy cost projections. The calculations result in favorable cost-benefit ratios of 2.3 for lighting 4-lane urban freeway sections, 1.4 for 6-lane sections, and 1.7 for 8- or 10-lane sections.

ACKNOWLEDGMENT

This paper has been prepared to summarize a portion of the findings of a project on the relation between illumination and freeway accidents. This 3-year study was commenced in 1967 and was financed principally by the Illuminating Engineering Research Institute, with aid from the Automotive Safety Foundation.

REFERENCE

1. Public Lighting Needs. Illuminating Engineer, Sept. 1966, pp. 585-602.

ANALYSIS AND DESIGN PROCEDURES FOR THE PENNSYLVANIA HIGHWAY LIGHTING NEEDS STUDY

James H. Herendeen, Jr., Pennsylvania Transportation and Traffic Safety Center, Pennsylvania State University

A highway lighting needs study was conducted to determine the financial implications of bringing Pennsylvania's highway lighting into compliance with the federal requirements resulting from the Highway Safety Act of 1966. The study involved the collection and analysis of data taken at a sample of more than 1,200 sites from the population of 4,591 sites that require lighting under the federal standards. Procedures were developed to facilitate the rapid design of lighting where none existed, the evaluation of lighting at existing installations, and the redesign of existing inadequate installations. Installation, maintenance, and energizing costs were then estimated. The techniques developed for the study are presented and discussed in terms of their value to the project. Applications of the design and analysis are then discussed in terms of their potential for time savings in preliminary design and cost estimation for highway lighting installations.

•THE FEDERAL Highway Safety Act of 1966 (1) called for the establishment of standards for highway lighting in recognition of the significance of highway lighting for the safety and operational efficiency of certain design elements of highways. The lighting warrants subsequently developed (2, 3) essentially require that adequate lighting be provided at all interchanges on expressways, at intersections of arterial streets in urban and suburban areas, at tunnels and long underpasses, and at all locations where accident records indicate a high incidence of nighttime accidents. Each state was required to prepare a plan that would ensure the lighting of such sites to avoid a reduction of federal-aid highway funds. To obtain the information necessary to develop a highway lighting plan, the Pennsylvania Department of Transportation commissioned the Pennsylvania Transportation and Traffic Safety Center of the Pennsylvania State University to conduct a study of lighting needs.

The purposes of the study were to determine the extent of highway lighting needs as defined by the federal warrants and to estimate the financial consequences of compliance with these standards. State highway lighting specifications were to be applied to the design and evaluation of sites that met federal warrants for lighting. The study was completed in December 1970 (4).

Initial phases of the project indicated that more than 4,500 sites within the commonwealth met federal warrants for lighting. Because time and budget constraints precluded the possibility of a complete investigation of all sites, a sampling procedure was developed to provide data from which adequate estimates of statewide lighting needs could be made. Data were subsequently collected for 1,236 sites from the total population of 4,591 sites. At each site within the sample, it was necessary to design lighting where none existed, to evaluate the adequacy of existing installations, and to redesign existing inadequate installations so that installation, maintenance, and energizing cost estimates could be made. Because of the number of sites involved, procedures had to be developed to facilitate the rapid determination of lighting needs at each of the 1,236 sampled sites.

The purpose of this paper is to describe the analysis and design procedures used to determine Pennsylvania's highway lighting needs. Emphasis is placed on the application of the techniques to the highway lighting needs study (3). However, the procedures appear to have applications beyond the specific requirements of the study. The possible

uses of the procedures and their potential for saving time and effort are discussed in the conclusions.

LIGHTING SPECIFICATIONS

Specifications for highway lighting in Pennsylvania (5) require a minimum average horizontal illumination of 0.8 footcandle at the pavement surface and a uniformity ratio of not more than 6 to 1 in any case and not less than 4 to 1 when obtainable within the 0.8 minimum footcandle illumination requirement. In definitional matters, the Pennsylvania specifications follow those developed by the Illuminating Engineering Society (6). Methods and procedures prescribed by the Illuminating Engineering Society are to be used to calculate average illumination and uniformity ratios. Pennsylvania specifications further state that standard design will consist of 400-W clear, color improved, or white mercury vapor lamps utilizing luminaires with type 2 or type 3 distributions mounted at no less than 30 ft. All nonstandard equipment must meet the average illumination and uniformity ratio requirements to be approved.

It was decided for purposes of this study to use standard 400-W luminaires mounted at 30 ft for lighting unlighted sites. Existing lighting facilities that utilized 175-, 250-, 400-, 700-, or 1,000-W mercury vapor lamps were to be accepted if they met average illumination and uniformity ratio specifications. Discussions with informed sources during the data collection effort indicated that there were few if any 250- or 700-W lamps in use in the commonwealth. Based on this information and the fact that most existing 250- and 700-W installations could be changed to 400- and 1,000-W installations respectively with very minor modifications, these 2 lamp wattages were excluded from further consideration. All other luminaire types were to be deemed inadequate except for fluorescent luminaries in tunnels or long underpasses. These assumptions formed the basis for development of the analytical procedures.

DATA

The data required to meet the objectives of the study consisted of 2 basic groups: cost data and data collected at sites. The cost data included installation, maintenance, and energizing costs. Installation costs were obtained from bid prices on contracts throughout the commonwealth. Approximately 150 cost components were tabulated by geographic area. Maintenance costs were obtained from contracts with companies providing highway lighting maintenance, including utility companies. Energizing costs were obtained from utility companies.

Data regarding the sites that met federal lighting warrants were collected from representatives of the Pennsylvania Department of Transportation and were supplemented with on-site investigations where "as-built" plans were not available. Programmed projects to be built before 1975 that met warrants for lighting were also included in the study. The data included the site location, the pavement dimensions to be lighted, and the quantity of existing lighting equipment at the site. If lighting was present, further information was recorded regarding the equipment type and placement, the mounting heights of luminaires, and the overhang of the luminaire beyond the pavement edge. A sketch of the layout was made with the luminaire locations and distances indicated where necessary for understanding of the configuration.

The 2 groups of data formed the basis of the analysis. It was necessary to evaluate the site data to determine the costs for installation, maintenance, and energizing that would be incurred in the process of compliance with federal standards and state lighting specifications. Estimates of statewide costs could be made for the entire population of such sites when the analysis of the sampled sites was completed.

DATA ANALYSIS

Because of the large number of sites that had to be examined, it was not practical to apply the raw cost data collected to each site. A simple technique had to be developed that would give fairly accurate results. It was found that installation costs could be estimated adequately by the following formula:

$$I = aX_1 + bX_2 + X_3 \tag{1}$$

where

I = total installation cost,
X_1 = cost per luminaire (including all cost elements that vary directly with the number of luminaires),
X_2 = cost per linear foot (including all cost elements that vary directly with site dimensions),
X_3 = lump-sum cost per installation (including all items that are independent of the size of the installation),
a = number of luminaires in a given design, and
b = total linear feet of roadway in a given design.

The values of X_1, X_2, and X_3 were found to vary somewhat with geographic location; X_1 decreased in large urban areas, and X_2 and X_3 increased in such areas. X_1 was also dependent on the lamp wattage. Maintenance costs were difficult to determine because of the varying policies regarding contracts and maintenance practices. A statewide average was finally decided on depending only on lamp wattage. Energizing costs were determined by calculating the power consumption of an installation (assuming certain system power losses) and a burning time of 4,100 hours/year.

Procedures for evaluating the site data were developed to provide inputs for the cost equations. Each site was examined first to determine whether it was lighted. If it was not lighted, lighting was designed for the installation. If it was lighted, the adequacy of the installation was determined. At inadequately lighted locations, a redesign was made that used as much of the existing equipment as possible. Installation costs were determined for designed and redesigned locations. Maintenance and energizing costs were then calculated for all sites. Figure 1 shows a flow diagram of this process.

The first decision could be made directly from information contained on the data sheets. The next step involved either the design or evaluation of lighting. These tasks and the redesign of inadequate existing installations were performed with a series of lighting design curves.

Lighting Design Curves

Average horizontal footcandles at the pavement surface are a function of lamp wattage, mounting height, luminaire spacing, pavement width, luminaire overhang, and other variables associated with the type of luminaire employed. The formula is

$$FC = (L \times U \times M)/(W \times S) \tag{2}$$

where

FC = average maintained footcandles;
L = end-of-life vertical lumens;
U = utilization factor (a function of mounting height, roadway width, and overhang);
M = maintenance factor to account for dirt accumulation on the luminaire (0.8 by Pennsylvania specifications);
W = roadway width to be lighted, in ft; and
S = luminaire spacing, in ft.

This formula suggests that, for a given wattage, mounting height and average footcandle illumination (and assuming a zero overhang), a graph can be plotted of maximum pole spacing versus roadway width. Such a graph should be a hyperbola because of the inverse relation between pavement width and pole spacing.

A further examination of the recommendations of the Illuminating Engineering Society indicates that type 2 light distributions should be used only up to pavement widths of 1.75 times the luminaire mounting height. From 1.75 to 2.75 times the mounting height, type 3 light distributions should be used. This information can also be easily

represented on a graph of maximum luminaire spacing versus roadway width for the conditions specified above.

The only remaining problem involves the effect of the uniformity ratio specification on the maximum allowable luminaire spacing. The effect cannot be determined by direct examination because the uniformity ratio must be calculated from isofootcandle diagrams. Isofootcandle diagrams are produced by manufacturers of specific equipment types and are developed according to procedures suggested by the Illuminating Engineering Society. Thus, any design curves developed from such data must be specific for that piece of equipment. The photometric data used to develop the curves for this study came from one manufacturer.

After several manual calculations were made to try to isolate the effect of the uniformity ratio on luminaire pole spacing, it was determined that the uniformity specifications controlled maximum spacing only for narrow pavement widths. The maximum uniformity (6 to 1) was always the controlling factor. In cases where the uniformity ratio was lower than 4 to 1, it was impossible to increase the ratio and still remain within the 0.8 minimum average footcandle requirement.

Calculations of the maximum spacing for a group of different luminaire wattages and mounting heights were made. A pavement width of 20 ft (30 ft for 1,000-W luminaires) was used as the minimum width to be considered. If the uniformity ratio governed the spacing of the minimum width, a trial-and-error procedure was followed to find the point where the minimum average illumination became the controlling factor. The next point checked was for a pavement width 1.75 times the mounting height, the point past which type 3 luminaires were required and behind which type 2 luminaires would be used. The last point used in development of the graph was one for which the pavement width was 2.75 times the mounting height, the maximum allowable pavement width for type 3 light distributions. The 3 or 4 points calculated were then plotted on the graphs with straight lines drawn between points as shown in Figures 2, 3, and 4.

As indicated earlier, one would expect the curves to be hyperbolic in shape. It was, therefore, necessary to test the accuracy of the linearity assumption. Between every pair of points used for producing the design curves, a check was made between the pole spacing predicted by the graph and a calculated pole spacing. Table 1 gives the results of this check. The maximum error was 4.17 percent with an average error of 1.06 percent. This was felt to be well within the desired accuracy for this study. It should be pointed out, however, that greater accuracy could have been obtained had more points been calculated for the graph. Another check was made to determine the difference in the pole spacing resulting from using another manufacturer's photometric data. The differences between the 2 sets of calculations were insignificant and could be attributed to the uncertainty of readings for the utilization factor. Thus, the design curves were accepted as valid for estimating the pole spacing required for lighting pavement areas of various widths.

It should be reiterated at this point that the lighting design curves were developed for the specific set of conditions listed below:

1. A minimum average maintained horizontal illumination of 0.8 footcandle;
2. A maximum uniformity ratio of 6 to 1 and a minimum of 4 to 1;
3. Medium, semi-cutoff, type 2 and type 3 clear mercury vapor lamps; and
4. A zero overhang of luminaire from the curb face.

The zero overhang assumption was used because it was found that a positive overhang (i.e., the luminaire is over the roadway) can be corrected for by the assumption that the pavement width is to be reduced by the amount of overhang with little loss of accuracy. Negative overhangs can be corrected for by adding the overhang to the pavement width. Other lighting specifications or equipment types would result in different lighting design curves.

Lighting Design for Unlighted Sites

For unlighted sites, the design curve for 400-W luminaires mounted at 30 ft was used. For interchanges, the lighting design curves were used to determine the number

Figure 1. Flow diagram of site data analysis.

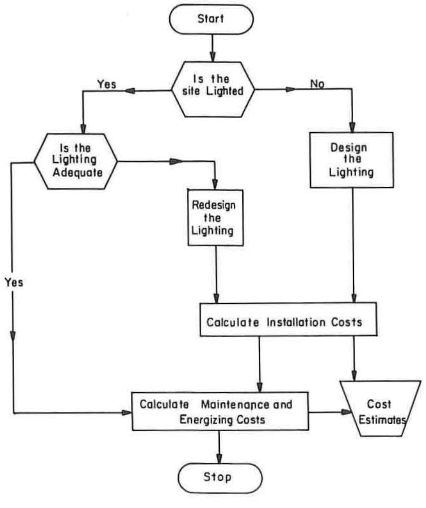


Figure 2. Design curves for 175-W luminaires.

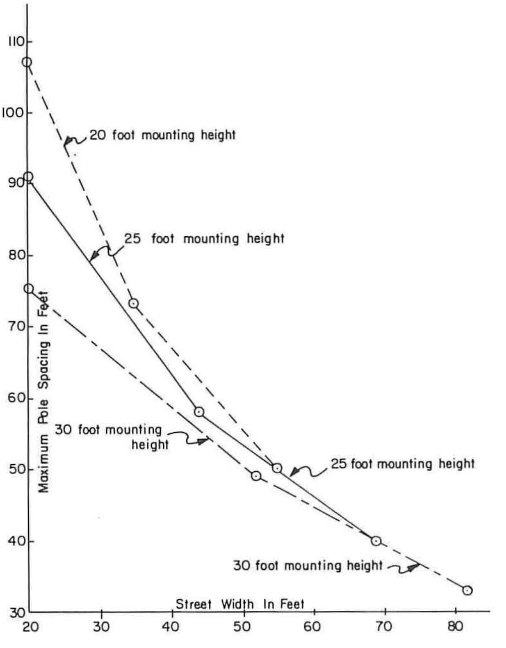


Figure 3. Design curves for 400-W luminaires.

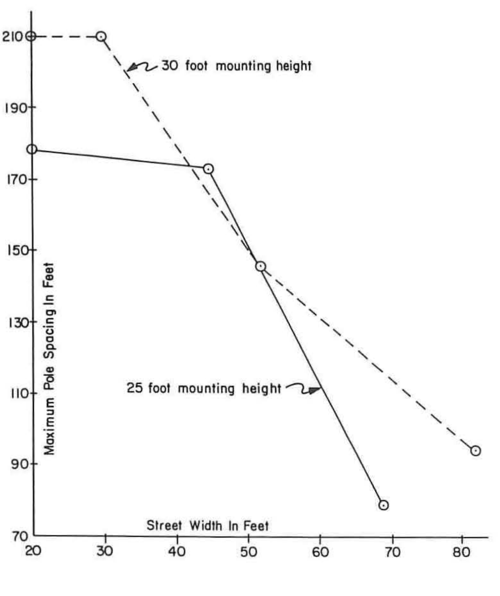
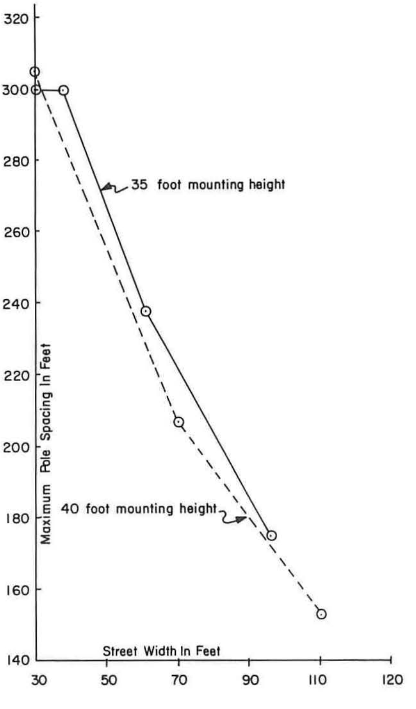


Figure 4. Design curves for 1,000-W luminaires.



of luminaires necessary to light the various lengths of different pavement widths. The total number of luminaires and the linear feet of roadway to be lighted were recorded. Ramps with widths of less than 20 ft were considered to be 20 ft wide. When medians were wider than 20 ft, the lighting was provided separately for each direction of traffic through the interchange area. High night accident sites (i.e., locations where accident records indicated a high incidence of nighttime accidents) were handled in a similar fashion.

Intersections posed a slightly different problem. Specifications suggest that the intersection area itself should be lighted, but they do not indicate how much beyond the intersection boundaries the lighting should extend. For this study, it was decided to light the intersection 5 ft beyond each of the boundaries. Thus, for a 24- by 24-ft intersection, two 24-ft pavement widths would be lighted for a distance of 34 ft. Notice that this procedure provides twice the lighting in the intersection area and follows recommendations by the Illuminating Engineering Society. The lighting design curves were used to determine the number of luminaires necessary to light intersections according to the indicated procedure. The routine nature of the design of lighting at unlighted locations allowed the analysis to be computerized. Nearly all new lighting designs were made with the computer and with the procedures developed; however, designs for tunnels and long underpasses had to be carried out on a site-by-site basis because of their unique characteristics.

Checking the Adequacy of Existing Installations

Data on existing lighting included the location of luminaires, the overhang, the pole spacing, and the luminaire type. As previously indicated, if the luminaires provided were not mercury vapor, they were considered inadequate. Mercury vapor luminaires were considered inadequate if not mounted high enough. The minimum allowable heights used in this study were 20 ft for 175-W lamps, 25 ft for 400-W lamps, and 35 ft for 1,000-W lamps.

From the data on luminaire type, mounting height, and pavement width, the maximum pole spacing was found from the design lighting curves. If the pole spacing measured in the field was less than, or equal to, the design pole spacing, the site was considered adequately lighted. The number and wattage of the existing luminaires were recorded for later use. If the pole spacing was greater than the maximum allowable, the sites were placed in the group of inadequately lighted locations. Tunnels and long underpasses had to be examined site by site because of the lack of height within the structure to provide a luminaire mounting height of more than 18 ft.

Redesign of Inadequately Lighted Sites

The redesign of inadequately lighted sites required a further categorization of what the redesign involved. Each redesign was placed in 1 of the following 5 categories:

1. New poles and luminaries added to existing installation,
2. Existing luminaries replaced on existing poles,
3. A combination of 1 and 2,
4. Redesign based on partial salvage, and
5. Redesign based on no salvage.

Figures 5, 6, 7, 8, and 9 show examples of the redesign process. The average spacing calculations shown were multiplied by the number of luminaires to indicate the length of roadway involved in the installation.

Figure 5 shows the addition of a luminaire to light the 20-ft legs of the intersection. Figure 6 shows the replacement of nonstandard luminaires with standard luminaires. Figure 7 shows a site where one of the existing luminaries is replaced on the existing pole. The partial salvage category is shown in Figure 8 where 2 of the existing poles were used to mount standard luminaires and a new luminaire was added to light the north-south legs of the intersection. Five existing poles were removed by this redesign. A site was placed in category 5, shown in Figure 9, only when luminaires were mounted at less than 20 ft or when the luminary was gas or fluorescent or when it was a

Table 1. Calculated and graphically determined maximum luminaire spacings.

Lamp Wattage	Mounting Height	Roadway Width	Graph Predicted	Calculated	Error[a] Amount	Error[a] Percent
175	20	30	84	84	0	0
175	20	45	61	59	+2	+3.39
175	25	30	77	76	+1	+1.32
175	25	55	50	48	+2	+4.17
175	30	35	63	65	-2	-3.08
175	30	60	45	44	+1	+2.27
400	25	40	174	169	+5	+2.96
400	25	55	131	131	0	0
400	30	33	201	199	+2	+1.00
400	30	40	181	176	+5	+2.84
400	30	65	124	124	0	0
1,000	35	45	280	280	0	0
1,000	35	75	212	214	-2	-0.93
1,000	40	55	243	236	+7	+2.97
1,000	40	85	187	189	-2	-1.06

[a]Average = +1.06 percent; maximum = +4.17 percent.

Figure 5. Lighting design for case 1.

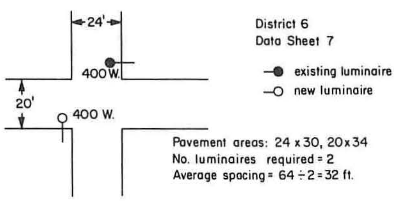


Figure 6. Lighting design for case 2.

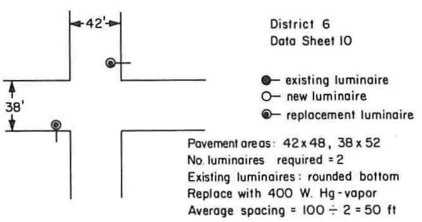


Figure 7. Lighting design for case 3.

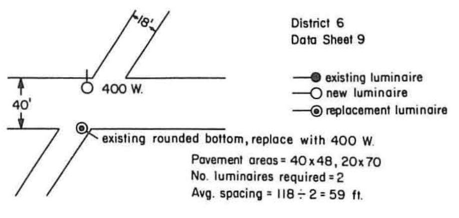


Figure 8. Lighting design for case 4.

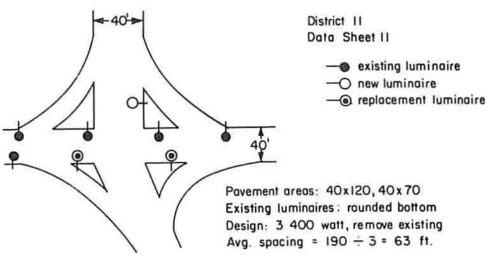
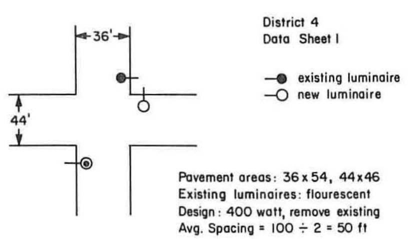


Figure 9. Lighting design for case 5.



nonstandard fixture type. In all other situations, at least 1 pole could be utilized in the new design.

For each of the redesign locations, the number of new luminaires, old luminaires, lamp wattage, and linear feet of the installation were recorded. All sites that were redesigned plus all sites that had no existing lighting were then examined to determine installation costs.

Installation Costs

Installation costs for sites with no existing lighting were calculated with Eq. 1. Previous steps in the analysis had determined the wattage and number of luminaires required for adequate lighting and the linear feet of roadway involved in the site; the geographic location was known from the data collection sheets. Thus, application of Eq. 1 was simply a "plug-in" process. For inadequately lighted locations (category 5, complete redesign, no salvage), the same process was followed. Costs for removing existing equipment were assumed to be covered by the scrap value of that equipment.

Costs for redesigned locations requiring the addition of luminaires to the existing equipment were calculated with a modified version of Eq. 1. Costs per luminaire and cost per linear foot were left unchanged, but the lump sum cost was prorated by the ratio of the new to the total luminaires. The resulting equation was

$$I = aX_1 + bX_2 + CX_3 \tag{3}$$

where I, a, X_1, b, X_2 and X_3 were defined earlier, and C = number of new luminaires/ total number of luminaires.

The installation costs for sites that required new luminaries on existing poles were calculated as follows:

$$I = dX_4 \tag{4}$$

where

I = installation cost;
d = number of new luminaries to be put on existing poles; and
X_4 = that portion of the cost per luminaire (X_1 defined above) involving the lamp, lamp housing, wiring, ballast, transformer base, and photoelectric cell costs.

Category 3 redesign utilized both Eqs. 3 and 4 to determine installation costs.

Installation costs for sites where some of the equipment could be utilized in the new design were calculated with Eq. 5. The equation assumes that one pole can be completely salvaged and that 25 percent of the remaining equipment not including X_4 (described above) could be utilized in the new design. The lump sum item, X_3, was not considered applicable because it essentially represents the cost of providing a power supply, which must have existed for the old installation.

$$I = aX_4 + 0.75\ (a - 1)\ (X_1 - X_4) + 0.75bX_2 \tag{5}$$

where all terms are defined above.

As indicated earlier, redesign for tunnels and long underpasses had to be calculated on a site-by-site basis because each site was unique. At this point in the analysis, the installation costs were available, indicating the equipment and construction costs of providing adequate lighting at each data point. The next step was to determine maintenance and energizing costs.

Maintenance and Energizing Costs

Maintenance and energy costs were calculated for all lighting at locations that met the federal standards for lighting both for existing lighting and for that additional equipment required to light existing inadequate and unlighted sites. Energizing costs were calculated as follows:

$$E = 0.41NWe \tag{6}$$

where

E = annual energizing costs;
N = number of luminaires;
W = power consumption (208 W for 175-W luminaires, 450 W for 400-W luminaires, and 1,058 W for 1,000-W luminaires); and
e = unit energy cost (2.25 cents/kW-h).

Maintenance costs were determined as follows:

$$M = Nm \tag{7}$$

where

M = annual maintenance cost;
N = number of luminaires; and
m = unit maintenance cost ($17/year for 175-W luminaires, $17/year for 400-W luminaires, and $21/year for 1,000-W luminaires).

As with earlier calculations, the maintenance and energizing costs for tunnels and long underpasses were handled independently because of their unique character. All other cost-estimating procedures were actually performed with the computer and the equations presented above.

The information available at this point in the analysis included the cost (installation, maintenance, and energizing) information for each site in the sample and the number of such sites within the state. All of the existing and future interchanges (planned for construction by 1975) and all tunnels and long underpasses were included in the sample data. Therefore, the statewide costs for these categories were simple additions of the site costs. The sample rate for intersections was 43 percent of the population and that for high night accident sites was 8 percent. Average costs per site type were calculated by the number of such sites in the state to obtain an estimate of the total costs for installation, energizing, and maintenance.

CONCLUSIONS

The procedures developed for the Pennsylvania highway lighting needs study would appear to have applications beyond their use in the study in 3 areas—lighting design, evaluation of existing lighting, and preliminary cost estimating. Some of the applications are obvious; however, further remarks seem appropriate.

The lighting design curves developed for the study give approximations of the maximum pole spacing for varying widths of pavement to be lighted. Each curve assumes a given level of illumination, a minimum and a maximum uniformity ratio, a given overhang of luminaire, photometric data from a specific manufacturer for a specific luminaire type, and other variables whose values are related to the luminaire type. These curves were deemed adequate for estimating the lighting requirements of currently unlighted sites and to evaluate the adequacy of existing lighting. The maximum error of the lighting design curves was found to be slightly more than 4 percent, which is well within the expected accuracy of other data used in the study. Similar lighting design curves could be developed for any particular set of lighting specifications and equipment and used in preliminary lighting design or for preliminary evaluation of existing lighting.

In the presentation of the lighting design curves, it was noted that further accuracy could have been obtained had more points been calculated in the pole spacing-roadway width plane. Taking this idea further, one asks why photometric data from manufacturers could not be in the form of lighting design curves instead of, or in addition to, isofootcandle diagrams and utilization curves. In fact, a similar idea utilizing different types of lighting design curves is illustrated in American Standard Practice for Roadway Lighting (6, p. 36). With the wide range of state specifications for lighting

currently in use, this might require the preparation of many separate curves for each luminaire type; however, the reduction of effort required to design lighting with this procedure would seem to be well worthwhile.

Designing lighting with the aid of lighting design curves would require one reading from the graph to determine pole spacing. Corrections for horizontal and vertical roadway curvature would then have to be applied. The use of isofootcandle diagrams and utilization factor curves to determine pole spacing requires a minimum of 2 graph readings plus a calculation to determine average illumination and as many as 9 graph readings and 3 calculations to check (for 3 points) the uniformity ratio. Then, should the uniformity ratio prove inadequate, a new estimate of the pole spacing must be made and the entire process repeated. Thus, the design curves could easily save hours in the design of lighting for an interchange. Similar savings would result from the use of such curves to evaluate the adequacy of existing lighting.

The cost estimating procedures developed for the highway lighting study appear to be valuable for the preliminary estimation of construction and equipment costs. Instead of a procedure that prices each item independently to estimate costs for final design, a formula similar to Eq. 1 could be developed to estimate costs for preliminary design. Such procedures should also result in time savings.

It is realized that the exact cost formulas and lighting design procedures presented in this paper might not be applicable to particular requirements beyond the scope of the study conducted. It is believed, however, that the basic techniques developed and employed in the study represent a starting point for the development of lighting design and cost estimating procedures that will greatly simplify the task of the highway lighting design engineer.

ACKNOWLEDGMENTS

This paper is based on work performed with cooperation and sponsorship of the Pennsylvania Department of Transportation and the National Highway Safety Bureau, U. S. Department of Transportation. The opinions, findings, and conclusions expressed in this publication are those of the author and do not necessarily reflect those of the department or of the bureau.

The original work on which this paper is based was accomplished by a team of investigators including Thomas B. Davinroy, Michael S. Bronzini, Ronald J. Slavecki, John C. Hayward, and the author, all associated with the Pennsylvania Transportation and Traffic Safety Center of Pennsylvania State University. Several of these individuals provided comments on technical matters described in the paper. Mr. Davinroy was on academic leave from the university at the time this paper was prepared.

REFERENCES

1. Highway Safety Act of 1966. U.S. Statutes at Large, Vol. 80.
2. National Highway Safety Program Standard 4.4.12: Highway Design, Construction and Maintenance. U.S. Department of Transportation, June 27, 1967.
3. National Highway Safety Standards. Insurance Institute for Highway Safety, Washington, D.C., 1967.
4. Highway Lighting Needs Study. Pennsylvania Transportation and Traffic Safety Center, Pennsylvania State Univ., University Park, Rept. TTSC 7018, Dec. 1970.
5. Design Manual 2. Bureau of Design, Pennsylvania Department of Highways, Harrisburg, Feb. 15, 1966.
6. American Standard Practice for Roadway Lighting. Illuminating Eng. Society, New York, 1964.

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